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## SUPERFLARES ON ORDINARY SOLAR-TYPE STARS

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### ABSTRACT

Short-duration flares are well known to occur on cool main-sequence stars as well as on many types of “exotic” stars. Ordinary main-sequence stars are usually pictured as being static on timescales of millions or billions of years. Our Sun has occasional flares involving up to  $\sim 10^{31}$  ergs that produce optical brightenings too small in amplitude to be detected in disk-integrated brightness. However, we identify nine cases of superflares involving  $10^{33}$ – $10^{38}$  ergs on normal solar-type stars. That is, these stars are on or near the main sequence, are of spectral class F8–G8, are single (or in very wide binaries), are not rapid rotators, and are not exceedingly young in age. This class of stars includes many of those recently discovered to have planets as well as our own Sun, and the consequences for any life on surrounding planets could be profound. For the case of the Sun, historical records suggest that no superflares have occurred in the last two millennia.

*Subject headings:* stars: flare — stars: late-type

### 1. INTRODUCTION

Astronomy has strong imperatives toward looking at exotic sources and having long exposure times, such that relatively fast variations on reputedly steady sources can easily be overlooked. Astronomers have a poor track record of realizing the existence of new classes of flares until many years after the first definitive observations, such as with ordinary flare stars, supernovae, W UMa stars, gamma-ray bursts, and Mira flares.

The search for fast flares on stars has two severe problems. First, a wide variety of instrumental or environmental artifacts can mimic a brightness increase (Schaefer 1989). Second, sufficiently rare events are difficult to detect. Nevertheless, stellar flares are known to come from many types of stars ranging from faint red dwarfs to many types of “exotic” stars (Schaefer 1989; Haisch, Strong, & Rodonò 1991).

We have been collecting reports in the literature on fast flares as a study of the background for searches of optical flashes from gamma-ray bursts. Some of the reported flashes come from G stars similar to our own Sun. The next section and Table 1 will describe the flares observed on nine ordinary main-sequence stars within half a spectral class of our Sun (F8–G8).

### 2. NINE SUPERFLARES

Groombridge 1830 (HR 4550) has the third largest proper motion on the sky and is the nearest belonging to the old ( $>10$  Gyr) halo population of our Galaxy. It has had extensive series of multiple-exposure photographs taken for astrometric studies. On 1939 April 27, a six-exposure plate from the Allegheny Observatory showed Groombridge 1830 to be significantly bright on four of its images (Beardsley, Gatewood, & Kamper 1974). The brightest image was 0.62 mag brighter than normal (in the

photographic magnitude system), and the flare duration was slightly longer than 18 minutes. Microdensitometry shows no change in the point-spread function for the flare images, the flare image centers were within 0.03 space of the expected position, and all other stars on the plate were constant. The total flare energy (in the blue band alone) is  $\sim 10^{35}$  ergs with an uncertainty of a factor of a few due to having only four points on the light curve.

$\kappa$  Ceti generally has the 5875.6 Å He I D3 line in absorption (Danks & Lambert 1985), yet it was seen in emission (Robinson & Bopp 1988) on 1986 January 24 in a spectrum taken at the Ritter Observatory with an intensified Reticon detector at a resolution of 0.25 Å and a signal-to-noise ratio of less than 75. The flare spectrum had a 40 minutes integration, while another spectrum that started 29 minutes later showed no He I emission. The emission line has all the hallmarks of a real feature: a narrow superposed telluric absorption line, the correct central wavelength for the radial velocity of  $\kappa$  Ceti, the expected shape for an emission line, no other anomalies in the flare spectrum, and no similar anomalies on any other spectrum. Big flares on our Sun also show the He I line in emission (Jefferies, Smith, & Smith 1959), with no other spectral changes within the range of the  $\kappa$  Ceti spectrum, so the transient line implies that  $\kappa$  Ceti was caught with a big flare. However, the He I line appears in emission in our Sun only when the small flare region is recorded on timescales comparable to the flare duration, typically 200 s (Jefferies, Smith, & Smith 1959). The  $\kappa$  Ceti spectrum records the *whole disk* of the star with an integration 12 times longer than the expected flare duration, so the size of the flare must have been very large. We can estimate its relative size by comparing the equivalent widths of the helium line above background for the  $\kappa$  Ceti flare (0.13 Å; Robinson & Bopp 1988) and a solar flare of importance 2 (0.72 Å; Jefferies, Smith, & Smith 1959). However, the equivalent width of the  $\kappa$  Ceti flare must be corrected for the

short duration during the long exposure (a factor of 12), while the equivalent width of the solar flare must be corrected to that of a whole-disk spectrum (a factor of  $\sim 3 \times 10^{-4}$  for the typical area of an importance 2 flare; see Allen 1976). The corrected ratios of equivalent widths is then  $\sim 7000$ , which presumably is comparable to the ratio of total energies. With a solar flare of importance 2 having  $10^{30.4}$  ergs (Allen 1976), we estimate the flare on  $\kappa$  Ceti to involve  $\sim 2 \times 10^{34}$  ergs.

MT Tau has only one known flare, which was discovered during a search for flare stars in the Pleiades at Tonantzintla Observatory (Haro & Chavira 1969). The flare appears as brightenings on a photographic plate through a  $U$  filter consisting of six 10 minute exposures with slight positional offsets between each exposure. G. Haro has rechecked the discovery plate and states that there is no doubt that MT Tau underwent a flare (Weaver & Naftilan 1973). MT Tau is not a Pleiades star since it has nonmember proper motion, does not show Ca II or hydrogen emission, and is 5 mag too faint for the Pleiades distance given its spectral classification (Weaver & Naftilan 1973). This classification is G5 V (confirmed by W. P. Bidelman), as measured with the Kitt Peak 84 inch (2.134 m) telescope with a dispersion of  $200 \text{ \AA mm}^{-1}$  (Weaver & Naftilan 1973). Based on a spectroscopic parallax, we adopt a distance of 2200 pc; the flare energy (in the  $U$  band alone) is of order  $10^{35}$  ergs with a factor of 10 uncertainty because of the limited light curve.

$\pi^1$  UMa was seen to flare in the X-ray band with the imaging detectors on the *EXOSAT* satellite (Landini et al. 1986). During a 3 hr observation, the star rose from its normal X-ray brightness to a peak in less than 8 minutes, followed by a decay with an  $e$ -folding timescale of 1000 s. The flare was detected independently with multiple detectors on *EXOSAT* at highly significant levels, from an imaged region centered on the quiescent emission while the background was stable, thus giving strong evidence that the star indeed had a flare. Spectral fits are consistent with an isothermal source of constant emission measure whose temperature peaked at around  $10^{8.0}$  K cooling to  $10^{7.4}$  K. The total energy in the range 0.1–10 keV is  $2 \times 10^{33}$  ergs.

S Fornacis is identified as a variable star for only one incident (Ashbrook 1959). On 1899 March 2, Lewis Swift had discovered a comet in the evening twilight, with confirmation from Lick Observatory. European observers were notified by telegraph, so as darkness fell on 1899 March 6, four observers tried to measure the position of Comet 1899a with respect to nearby bright stars. Three of the observers all independently reported one particular comparison star to be roughly 3 magnitudes brighter than normal, making it hard to recognize the field although the measured astrometric positions were correct for the quiescent star. These observers (in Vienna, Austria, Arcetri, Italy, and Bamberg, Germany) all reported the star bright from 7:37 to 7:54 UT. The observers (J. Holetschek, A. Abetti, and E. Hartwig) were highly experienced and well respected. While the photometric accuracy of the visual reports is not high, the existence of a 3 magnitude anomaly is a very significant claim. The independent discovery by three widely separated and skilled observers and the three astrometric positions remove all doubt about that S For was flaring. The duration of the flare is constrained by the lack of a reported anomaly by E. Millosevich in Rome (who also used S For as a comparison star) at 7:13 UT and the normal brightness

shown on Harvard plate I22535 at 13:20 UT. So the duration of the flare is from 17 to 367 minutes. The *Hipparcos* distance to S For is 147 pc with a 25% uncertainty, and the flare energy (in the  $V$  band alone) is roughly  $2 \times 10^{38}$  ergs with an uncertainty of about 1 order of magnitude due to poor light-curve information.

BD +10°2783 was fortuitously in the field of view of Markarian 841 during a series of observations (I. George & S. Drake 1998, private communication) with the *ROSAT* PSPC on 1992 January 21. This series consisted of four intervals (with 510, 580, 830, and 830 s of data) over a 10 hr period. In the first interval, BD +10°2783 was brightening from 1.5 to 1.8 counts per second. The second, third, and fourth intervals (starting 93, 191, and 583 minutes after the first) show the flux at 0.29, 0.20, and 0.13 counts per second, respectively. The excess counts above quiescence totaled 1500 in the four observed time intervals. A spectral analysis is consistent with a coronal plasma with a dominant temperature of 1.4 keV. For a distance of 150 pc (based on a spectroscopic parallax), this corresponds to a flare energy in the range 0.1–2.0 keV of  $3.0 \times 10^{34}$  ergs for just the four observed time intervals alone (I. George & S. Drake 1998, private communication). If the time coverage had been complete and the flare light curve had had an exponential decay, then the actual X-ray energy would have been an order of magnitude higher.

$\alpha$  Aquilae was monitored with accurate  $B$  and  $V$  photometry from 1979 May to 1980 September as part of a broad program following many stars at the David Dunlap Observatory (Bakos 1983). On two occasions, the star showed significant flares. The first flare (1979 September 20) had a  $V$  amplitude of 0.09 mag, no significant change in color, and a duration of less than 5 days. The star was measured to be bright in both the  $B$  and  $V$  bands on a single night. The second flare (1980 July 24) had a  $V$  magnitude of 0.09 mag, no significant color change, and a duration of roughly 15 days. The star was measured to be bright on four separate nights in both the  $B$  and  $V$  filters, although the duration and number of the flares are not well constrained. The energy of the second flare (in the  $B$  and  $V$  bands alone) is estimated to be  $9 \times 10^{37}$  ergs.

$\epsilon$  Serpentis was also followed photometrically during 1979 and 1980, showing significant flares on three occasions (Bakos 1983). The  $V$ -band amplitudes were 0.05, 0.09, and 0.07 mag for durations of less than 11, less than 25, and 3–15 days, respectively. The colors for each flare were unchanged from normal, except that the last flare is bluer (with a  $B$ -band amplitude of 0.12). The first two flares were detected on only one night each in both  $B$  and  $V$ , while the third flare was detected on two nights also in  $B$  and  $V$ . For a 3 day duration, the flare energy (in the  $B$  and  $V$  bands alone) is  $7 \times 10^{37}$  ergs.

UU CrB was observed as a comparison star for a nearby eclipsing binary (Olson 1980). The photoelectric measurements were made with five filters (from ultraviolet to the far red) over 12 nights (16.4 hr total) with repeated cycling between variable, comparison star, check star, and sky. On 1980 May 21, a flare was recorded near the start of its rise, with the peak 45 minutes later. This peak was followed by a decay with a speed comparable to that of the rise, although the photometry stopped a dozen minutes after the peak. A total of 27 independent measures in five filters (interspersed with check star measures) show the flare. Pairs of magnitudes in all five filters taken 2 hr later showed the star at its

quiescent light level. The amplitudes in the  $u$ ,  $v$ ,  $b$ ,  $y$ , and  $I_K$  filters are 0.18, 0.11, 0.10, 0.05, and 0.30 mag, respectively. The colors of the excess light are extremely blue shortward of 5500 Å and extremely red longward of 5500 Å. The total energy (across the observed optical bands) was  $7 \times 10^{35}$  ergs (Olson 1980).

### 3. SUPERFLARE PROPERTIES

The flare energy from our nine stars can be compared to flares on our Sun. (Distances used for these calculated energies are from *Hipparcos* and are accurate to better than 10%, except as noted in the previous section.) Typical solar flares have energies of  $10^{29}$  ergs, the largest white-light flare has roughly  $3 \times 10^{31}$  ergs in the visible, and the largest X-ray flare had an energy of  $\sim 2.5 \times 10^{31}$  ergs (Haisch, Strong, & Rodonò 1991). The six optical flares from Table 1 have energies ranging from  $1 \times 10^{35}$  to  $9 \times 10^{37}$  ergs over various fractions of the visible range, and this is more than 3000 times the most energetic solar flares integrating over the entire visible range. Bolometric corrections will substantially increase the total energy emitted by the flares. The two X-ray flares from Table 1 have X-ray energies roughly 100 times and 1000 times the largest solar X-ray flare. The spectroscopic flare on  $\kappa$  Cet has an estimated energy 7000 times that of a solar flare of importance 2. In all cases the conclusion is that they are  $\geq 100$  times that of the largest solar event, even allowing for the uncertainties in the measured energies. This is our justification for calling these flares “superflares.”

Could the superflares arise from some previously known stellar flare mechanism on some unknown star hidden in the system? Low-luminosity stellar flare sources (ordinary red dwarf flare stars) can easily reside in the systems without notice, but the observed flare properties are all wrong for this explanation. In particular, three of the flares are red or neutral in color, the two X-ray flares have unreasonable energetics, the six optical events require implausible amplitudes, while all events have durations greatly longer than those of flare stars. Known classes of stellar flares that are similar to the observed superflares (RS CVn and BY Dra flares) could arise on companion stars to the primary as part of a double or triple system; however, their luminosity is roughly equal to that of the primary star and would definitely be identified in the study reported below. So the superflares must arise either from a previously unknown mechanism upon hypothetical companions or arise upon the primary star.

The nine superflare stars appear to be ordinary stars like our Sun, but is it possible that they are very young, rapidly rotating, or in a close binary system? This is an important question since there are known classes of stellar flares in systems with G star components that are characterized by these properties (T Tauri stars, RS CVn stars, BY Dra stars, and cataclysmic variables). To answer this question, we have collected measurements of quantities that are sensitive to youth, rotation, and duplicity (Table 2). The spectral type, luminosity class, the lithium equivalent widths, rotational  $v \sin i$ , and duplicity are from recent literature refer-

TABLE 1  
SUPERFLARES

Star	Detector	$V_{\text{normal}}$	Amplitude	Duration	Energy (ergs)
Gmb 1830 .....	Photography	6.45	$\Delta B = 0.62$ mag	18 minutes	$E_B \sim 1 \times 10^{35}$
$\kappa$ Cet .....	Spectroscopy	4.83	EW(He) = 0.13 Å	$\sim 40$ minutes	$E \sim 2 \times 10^{34}$
MT Tau .....	Photography	16.8	$\Delta U = 0.7$ mag	$\sim 10$ minutes	$E_U \sim 1 \times 10^{35}$
$\pi^1$ UMa .....	X-ray	5.64	$L_X = 10^{29}$ ergs $s^{-1}$	$> \sim 35$ minutes	$E_X = 2 \times 10^{33}$
S For .....	Visual	8.64	$\Delta V \sim 3$ mag	17–367 minutes	$E_V \sim 2 \times 10^{38}$
BD + 10°2783 .....	X-ray	10.0	$L_X = 2 \times 10^{31}$ ergs $s^{-1}$	$\sim 49$ minutes	$E_X \gg 3 \times 10^{34}$
$\sigma$ Aql .....	Photometry	5.11	$\Delta V = 0.09$ mag	$\sim 5$ –15 days	$E_{BV} \approx 9 \times 10^{37}$
5 Ser .....	Photometry	5.06	$\Delta V = 0.09$ mag	$\sim 3$ –25 days	$E_{BV} \approx 7 \times 10^{37}$
UU CrB .....	Photometry	8.63	$\Delta I = 0.30$ mag	$> \sim 57$ minutes	$E_{\text{opt}} = 7 \times 10^{35}$

TABLE 2  
ARE THE STARS LIKE OUR SUN?

Star	Spectrum	Li EW (mÅ)	$v \cdot \sin i$ (km $s^{-1}$ )	$S$	$L_X$ (ergs $s^{-1}$ )	Companion
Gmb 1830 .....	G8 V	4.0	1.3	0.188	$< 4 \times 10^{27}$	Single
$\kappa$ Cet .....	G5 V	38	8	0.366	$8.2 \times 10^{28}$	$V = 9.3, a = 269''$
MT Tau .....	G5 V	...	...	...	$< 2 \times 10^{32}$	Single
$\pi^1$ UMa .....	G1.5 Vb	96	9.7	0.367	$9.3 \times 10^{28}$	Single
S For .....	G1 V	34	7	...	$< 2 \times 10^{29}$	$V = 9.3, a = 0.3''$
BD + 10°2783 .....	G0 V	$< 23$	4	...	$< 9 \times 10^{29}$	Single
$\sigma$ Aql .....	F8 V	63	3.9	0.148	$< 2 \times 10^{28}$	$V = 13.4, a = 22''$
5 Ser .....	F8 IV–V	$< 3$	2	0.140	$< 3 \times 10^{28}$	$V = 9.7, a = 11''$
UU CrB .....	F8 V	$< 12$	6	...	$< 3 \times 10^{29}$	Single

enced in SIMBAD. We have observed the lithium equivalent widths and  $v \sin(i)$  for S For, UU CrB, and BD +10°2783 with the HYDRA spectrograph on the WIYN 3.5 m telescope in 1996 April. The calcium H and K activity index ( $S$ ) is defined in Baliunas (1995). The distances are all from *Hipparcos* parallaxes except for the distances to MT Tau and BD +10°2783 which are based on spectroscopic parallaxes. The X-ray luminosities are from *ROSAT* for 0.1–2.5 keV. Ordinary stars (as distinct from exotic sources such as pre-main-sequence stars, RS CVn stars, BY Dra stars, and cataclysmic variables) can be reliably distinguished by the simultaneous criteria that the lithium equivalent width must be less than 100 mÅ, the  $v \sin(i)$  is less than 10 km s<sup>-1</sup>, the  $S$  value is less than 0.5, the X-ray luminosity is less than  $3 \times 10^{29}$  ergs s<sup>-1</sup>, and no radial velocity variations are detectable. All nine of our superflare stars pass these tests as not being very young, rapidly rotating, or in a close binary, so we can definitely rule out all known classes of stellar flares.

Since these stars are F8–G8, on the main sequence, single (or at least only in very wide doubles), and have no apparent large differences from our Sun, we feel justified in calling the superflare stars “solar-type.” This is not to say that the stars have properties identical to those of our Sun; for example, Gmb 1830 and 5 Ser are substantially older than our Sun, while  $\kappa$  Cet and  $\pi^1$  UMa are  $\sim 1$  Gyr in age. *Hipparcos* parallaxes indicate that three stars (S For, 5 Ser, and  $\alpha$  Aql) might be at or perhaps just barely past the main-sequence turnoff. Nevertheless, two of our stars ( $\kappa$  Cet and  $\pi^1$  UMa) have both been independently identified by three groups as among the “best true solar twins” and “solar analogs” (Cayrel De Strobel 1996; Gaidos 1998; DeWarf et al. 1998).

How frequently does an average solar-type star suffer a superflare? With no adequate systematic studies, any rate estimate must be crude. X-ray satellites have logged  $\sim 20$  yr of imaged observations over typical fields of view of  $\sim 1$  deg<sup>2</sup> with approximately one G star per square degree brighter than  $V = 10$  mag (Allen 1976) resulting in two reported flares, suggesting a crude average recurrence timescale of a decade. Of the 9110 naked eye stars in the Yale Bright Star catalog (Hoffleit 1982), 4% are main-sequence stars with spectral class F8–G8, and five have reported superflares in Table 1. An order-of-magnitude estimate is that these stars have been monitored over the last century for  $\sim 1$  yr of time for which a superflare could have been detected. If so, then the average recurrence timescale is of order a century. The usual long-exposure patrol plates are insensitive to flares (Schaefer 1989), but series of short exposures with positional offsets are good for discovering flashes from stars. Of order  $10^4$  of these chain photographs have been taken, each typically 1 hr in duration covering  $\sim 10$  deg<sup>2</sup> to typically 15 mag recording  $\sim 10^3$  solar-type stars (Allen 1976). With these estimates, the two events from Table 1 detected with chain photography imply a recurrence timescale of order 600 yr. (The search for gravitational lensing events from MACHOs has not yet placed any useful limits on the superflare rate because G-type main-sequence stars are below the thresholds for bulge and LMC stars and also because the usual detection criteria require  $\geq 6$  times when the star is  $> 0.32$  mag bright.) While these timescales are accurate only to within 1 or 2 factors of 10, it is clear that we are dealing with an *average* recurrence time of

decades or centuries. If only some fraction of the solar-type stars flare, then the rate might be higher.

What is the frequency of the superflares on our Sun? This need not equal the *average* value for similar stars. Any superflare in the last 150 yr of scientific monitoring of the Sun would definitely have been recognized. Within historical times, a superflare would presumably have been recorded as a bright (oddly colored?) Sun or a short intense heat wave. Perhaps the most general and reportable phenomenon would likely be a world-spanning aurora visible to equatorial latitudes. In the absence of such reports, the Sun has likely not had any superflares in the last two millennia. On longer timescales, there are few ways to identify all but the most powerful superflares, although we are reminded of the Greek myth of Phaëthon wherein the chariot of the Sun drove too close to the Earth and scorched the Sahara desert. In all, we conclude that our Sun has a significantly lower superflare frequency than the average for the stars in our sample, and perhaps the Sun’s rate is zero.

#### 4. CONSEQUENCES

Both superflares and planets are common around normal solar-type stars, so it is natural to examine the consequences of superflares on planets. For a superflare with a 1 hr characteristic duration, the luminosity from the flare will equal the normal luminosity from the star for a  $10^{37}$  ergs event. The flux deposited by a single flare on a planet is  $3.5 \times 10^7$  ergs cm<sup>-2</sup> for a  $10^{35}$  erg superflare at a distance of 1 AU. On a rocky surface, this flux is much too low to cause melting or other geophysical effects. On an icy surface, this flux will lead to large-scale melting and the formation of flood plains for superflares with greater than  $\sim 10^{38}$  erg (assuming a composition dominated by water ices, a characteristic absorption depth of 1 cm, and an orbit with radius 5 AU).

The effects of a superflare on a planet with an atmosphere will depend critically on the energy and spectrum of the flare and on the structure of the atmosphere. Possible effects include temporary heating, worldwide aurora, the temporary breakup of an ionosphere, and ozone depletion. The ionizing radiation of gamma rays, X-rays, and energetic protons will not reach the ground but will be absorbed in the upper atmosphere. For an Earthlike atmosphere, this will create nitrous oxides at high altitude, which will start a cycle of ozone destruction that will last long past the end of the superflare. An event with  $\sim 10^{36}$  ergs of ionizing energy will result in roughly 80% ozone loss for longer than a year, with normal stellar ultraviolet light then irradiating the surface (Ruderman 1974).

With either a causal (Rubenstein & Schaefer 1999) or a casual connection between planets and superflares, the superflares might play a significant role in the evolution of any life on the surface of planets or their moons. From the last paragraph, the effects of temperature rises and ultraviolet light at the surface could prove to be damaging to existing life, perhaps to the extent of causing extinctions. Alternatively, the superflares might provide an energy source to create organic molecules (such as the lightning in the Miller-Urey experiment) over the star-facing hemisphere as the first step in the creation of life.

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